Acoustic Tomography of Natural Bubble Fields and Ship Wakes

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LONG-TERM GOALS

The goals include development and refinement of tomographic algorithms with applications to the quantitative measurement of bubble fields. Natural bubble fields have a profound effect on sonar systems while ship wakes have a debilitating impact on the effectiveness of anti-torpedo torpedo systems. This research investigates the use of acoustic tomography and effective medium models for wave propagation in bubbly water as a means of determining physical properties of bubble fields.

OBJECTIVES

The scientific objectives seek to establish methods to determine physical properties of bubbly water from *in-situ* acoustic measurements. Acoustic tomography has been used to reconstruct images of the attenuation such that spatial dependence and magnitude are estimated. The tomographic algorithms are extended to reconstruct estimates of the group slowness (i.e., inverse of the group velocity).

APPROACH

Rouseff et al.[1] have implemented a discrete data/continuous wave tomographic algorithm to invert measured amplitude data to determine the attenuation coefficient for bubbly water. They have applied the algorithm to data collected during the “Delta Frame Experiment” (DFE).[2,3] Runs 5 and 7 occurred during significant wave breaking and rip current activity. Of particular interest is run 5 because it coincided with experiments by other researchers[4], which provide independent measurements of the bubble field. During FY01, the research had several components. First, the analysis initiated by Rouseff et al. on attenuation data from the DFE was applied to other runs. Second, the tomographic algorithm was extended to the reconstruction of the spatial variation in group slowness. While the attenuation algorithm required amplitude information from the received signals, the group slowness used the time-of-flight of pulses from the sources to receivers. Proper estimation of the time-of-flight for a pulse required careful data reduction because of the dispersive nature of a bubbly medium. The final component of the FY01 effort initiated the development of a method to invert measured group slowness and attenuation to physical characteristics of the bubble field such as a bubble size distribution. The

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14. ABSTRACT
The goals include development and refinement of tomographic algorithms with applications to the quantitative measurement of bubble fields. Natural bubble fields have a profound effect on sonar systems while ship wakes have a debilitating impact on the effectiveness of anti-torpedo torpedo systems. This research investigates the use of acoustic tomography and effective medium models for wave propagation in bubbly water as a means of determining physical properties of bubble fields.

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wave propagation model for a dilute bubbly liguid given by Commander and Prosperetti[5] was extended to include all orders of multiple scattering.[6]

WORK COMPLETED

Several components of the proposed work were completed. First, raw acoustic data from the DFE for runs 5, 6, and 7 were obtained from Caruthers of NRL-SSC. The first component culminated with the development of algorithms to extract amplitude information from the data to re-evaluate the attenuation reconstructions of Rouseff et al.[1] The amplitude information was extracted by a spectral method, which confirms an alternative method used by Caruthers.[2,3] Second, the quality of DFE data was assessed by inspecting the amplitude information for each source/receiver pair and for all pings in runs 5, 6, and 7. Third, a method was devised to extract time-of-flight information for individual frequency pulses in the DFE signals. This component represents the majority of the work completed because the complexity of DFE signals and the dispersive properties of the bubbly water mandated careful attention to the extraction. The time-of-flight estimation is discussed below. The final component of the work applied the tomographic algorithm to the time-of-flight data to reconstruct the group slowness.

RESULTS

The delta frame was a triangular array consisting of 2 sources (A and B) and 8 receiver [1–8 (See Fig. 2)]. The length of a side of the array was 9.4 m. The sources were located at 2 vertices and the receivers were distributed on the sides of the triangle. The sources and receivers were coplanar and located about 2.8 m above and parallel to the sea floor. The water depth was 4.3 m and the array was 300 m offshore. Each source transmitted two signals containing four pulses. The low frequency signal contained 98, 78, 59, and 39 kHz pulses with a 0.1 ms duration and a nominal spacing of 0.02 ms. Each frequency pulse had a modified Hanning envelope to reduce ringing. The high frequency signal contained 244, 186, 146, and 117 kHz pulses. A run consisted of the consecutive transmission of the two signals from each source and the recording of the signals at each receiver. The received signals were sampled at 625 kHz with 12-bit resolution and contained 512 points. A typical run was 90 minutes with a repetition rate of one ping per second. Figure 1 depicts a signal from the DFE.

Variations in the index of refraction in dilute bubbly water are relatively small, and hence the acoustic energy principally travels along straight paths between source/receiver pairs. Rouseff et al. have applied ray tomography to the attenuation of signals collected during DFE. A key feature of tomographic algorithm was that the inversion smeared a back-projected ray in space, which yielded a smooth image. A brief description of the algorithm is given here while the details are available in Ref. 1. It is assumed that an observable

$$d_i = \int D(\mathbf{r}_i) d\eta_i + \epsilon_i \tag{1}$$

can be expressed as a path integral of some quantity, $D(\mathbf{r}_i)$, and additive noise ϵ_i. Figure 1 (and other raw data not shown) suggested that the signal to noise ratio was fairly high, so ϵ_i is suppressed. The measured total loss or time-of-flight for the ith source/receiver pair is d_i, and $D(\mathbf{r}_i)$ is the spatially dependent attenuation per unit length or group slowness. The coordinate vector, $\mathbf{r}_i = x_i\mathbf{e}_x + y_i\mathbf{e}_y$, is constrained to lie along the ray path and $d\eta_i$ is an infinitesimal increment. An estimate for $D(\mathbf{r})$ is

$$\hat{D}(\mathbf{r}) = [M_{ij}]^{-1} d_j \psi_i(\mathbf{r}) \tag{2}$$

where

is the ith back-projected
correlation function, which
represents the inverse

such that $R(|\mathbf{r}_i - \mathbf{r}_j|)$
function was investigated
length is L and it is the

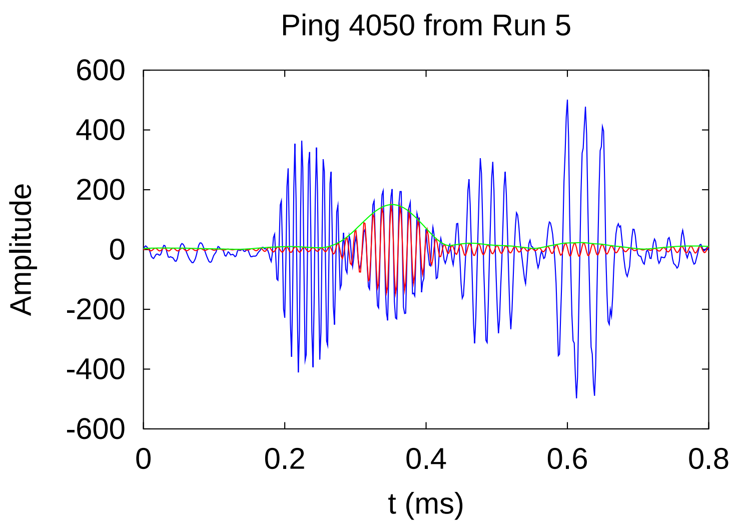

Figure 1: Low frequency signal produced by source A and received by receiver 6. Receiver 6 was located near the midpoint of the side opposite source A giving a 8.13 m path length. The ping occurred 4050 seconds after run 5 was initiated and it coincided with modest surf-zone activity. The 78 kHz pulse extracted from the raw data and its envelope are also shown.

Before tomographic reconstructions of the attenuation can be performed, the raw data was pre-processed. The power spectral density, computed via a radix-2 FFT, was numerically integrated over a 10 kHz bandwidth centered at each of the DFE frequencies. This gave an estimate of the received intensity for each frequency and for each source/receiver pair. But, the total loss due to the bubbles was required. An *in-situ* calibration was performed by scanning an entire run (i.e., 5200 pings) for the maximum received intensity for each frequency and source/receiver pair. Because bubbles can only increase the attenuation, these maximum received intensities were representative of a “bubble-free” environment. The total loss for any given ping is estimated by subtracting the received intensity for each frequency and source/receiver pair from the appropriate maximum received intensity.

Estimates of a travel time required additional processing. The raw data was transformed to the frequency domain by a FFT and a filter was applied to the spectrum to isolate a specific frequency pulse. Although numerous filtering schemes were investigated, the following filtering was used. A synthetic pulse with a Gaussian envelope, $\exp[-q(t-t_0)^2/t_0^2]\sin[\omega(t-t_0)]$, was created where the pulse duration

was 0.2 ms. The constants
optimizations. The synthetic
magnitude of this transform
was manipulated to compute
extracted pulse and its

Bubbly water exhibits
Acoustic energy within
peak of a pulse envelope
expedient approach of
estimated arrival times
reduce the effect of this
by Dahl[4] that the waves
vertical motion that w
inappropriate for both
estimated by fitting a quadratic
Finally, the DFE set a
pulses within a signal
available from the raw

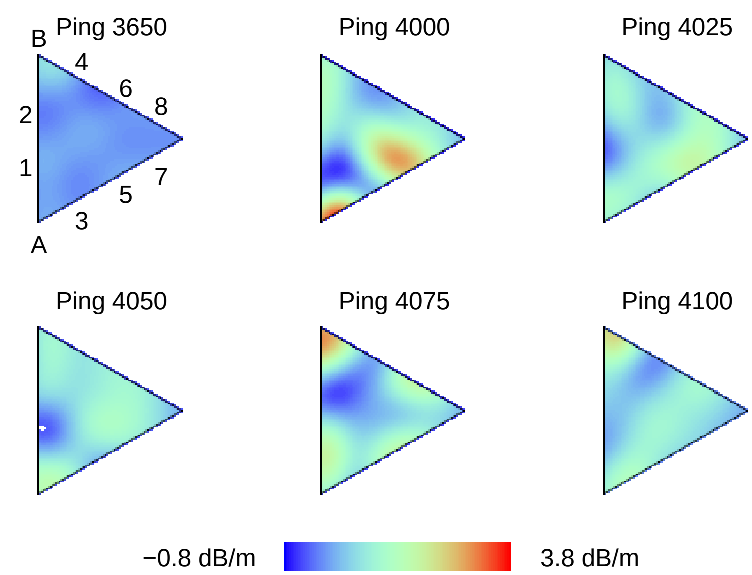

Figure 2: A sequence of reconstruction of the attenuation coefficient are depicted for data collected during a modest rip current event. The color bar contains 128 levels that uniformly span the 4 dB/m range.

Figure 2 contains the tomographic reconstructions of the attenuation coefficient for pings 3650, 4000, 4025, 4050, 4075, and 4100 at 78 kHz. The total loss was estimated for these pings and used as d_j, $j = 1, \cdots, 15$, in Eq. (2). The ray path from source B to receiver 1 is not included in the reconstruction because it is a redundant ray path. A Gaussian correlation function was assumed for the medium with a correlation length of $L = 2$ m. The reconstruction of ping 3650 is fairly uniform with $-0.32 < \alpha(\mathbf{r}) < 0.78$ dB/m throughout the image because ping 3650 occurred during a quiescent period when few bubbles are expected. The remaining pings span a 100 s rip current event. It is evident from pings 4050, 4075, and 4100 that a local bubble-free region has been advected from the left edge of the delta frame to top right leg. Additionally, pings 4000 and 4075 contain regions where $\alpha(\mathbf{r})$ exceeds 3 dB/m. Inspection of these reconstruction reveals spatial structure on the order of a meter. Comparison of pings 4000 and 4025 demonstrates that this structure under went significant changes over an elapsed time of 25 s, and inspection of several consecutive pings after 4000 showed similar spatial variations.

Reconstruct of the group slowness for the same pings were also computed (not shown, here). The choice of L used in the inversion for attenuation coefficient was constrained by the requirement that $\alpha(\mathbf{r})$ should be positive. No such constraint applied to the group slowness. The reconstructions showed little variation in the predicted group slowness. In fact, the group slowness in the central region of the delta frame is close to 0.664 s/km, which is the inverse of the measured sound speed in "bubble-free" water. An effective medium model for wave propagation in bubbly water suggests that the structure observed in Fig. 2 for the attenuation coefficient should be reflected in a group slowness reconstruction. The lack of structure may be a consequence of the estimates for the time-of-flight of the wave packets. A computation of the group slowness over the DFE frequency range of 0 to 300 kHz predicted values of the slowness that span 0.62 to 0.69 s/km. The dispersion that occurred during this rip current event appears to be too weak to affect a measureable change in pulse travel time particularly with the coarse time increment of $\Delta t = 1.6\ \mu$s in the DFE. The high and low frequency signals used in the DFE are better suited to an attenuation measurement over a broad frequency than a time-of-flight measurement of the wave packets.

IMPACT/APPLICATIONS

The current research and results have implications for sonar systems operating in bubbly water. The bubble size distribution in mature bubble clouds spans a range of radii from approximately 30 to 150 microns with the peak in the distribution occurring near 80 micron. The range of resonance frequencies for these bubbles is approximately 20 to 120 kHz. The void fractions of these clouds are sufficiently large that multiple scattering must be considered. Tomographic image reconstruction of attenuation and group slowness in the bubbly water provides a means to determine the spatial variation in the bubble field. By coupling the reconstructed images with effective medium models for wave propagation in bubble liquids, optimal operation frequencies for sonar systems may be determined.

TRANSITIONS

RELATED PROJECTS

The current research has direct extensions to the Bubbles and Acoustics Communications Initiative currently under planning by ONR Code 321 OA. Additionally, the effective medium model for wave propagation in bubbly liquids [4] has direct implication for the research of Dr. Ronald A. Roy at Boston University as well as others where multiple scattering effects cannot be ignored.

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